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A NUMERICAL ANALYSIS OF THE EFFECT OF EROSION STRAIN ON BALLISTIC PERFORMANCE PREDICTION

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ABSTRACT

This memorandum examines the effect of the erosion strain parameter on the numerical simulation results of the penetration of two different projectile/target systems. This parameter permits the failure of the material and numerically allows the penetration of the target. The first system examined consists of the SS109 5.56-mm bullet striking a 10.8-mm 6061-T6 aluminium target while the second system consists of the M80 7.62-mm bullet striking a 76.2-mm semi-infinite aluminium target. For the SS109 5.56-mm case, it was found that the ballistic limit increased significantly as the erosion strain is increased above 0.4, but as it reaches about 1.3, it becomes less and less dependent on the erosion strain. In the case of the M80 7.62-mm projectile, both the depth of penetration and crater volume were examined as a function of the erosion strain. For erosion strains ranging from 0.5 to 3.0 a significant dependence of the penetration results on the erosion strain was observed. For erosion strains above 3.0, most of the penetration results were observed to be within an acceptable range of the experimental value.

RÉSUMÉ

Dans ce mémorandum, on étudie l'effet du paramètre d'érosion sur les résultats obtenus à partir de simulations numériques de pénétration de deux différents systèmes de cible/projectile. Ce paramètre contribue à la rupture du matériel et facilite ensuite la pénétration dans la cible. Le premier système est composé d'une plaque d'aluminium 6061-T6 d'une épaisseur de 10,8 mm subissant l'impact d'un projectile SS109 de 5,56 mm. Le deuxième système est composé d'une cible d'acier de blindage semi-infini d'une épaisseur de 76,2 mm frappée par un projectile M80 de 7,62 mm. Dans le cas du SS109 de 5,56 mm, l'étude montre que la limite balistique augmente considérablement lorsque le paramètre d'érosion dépasse 0,4. Cependant, lorsque le paramètre d'érosion atteint 1,3, la limite balistique devient de moins et moins dépendante de ce dernier. Dans le cas de M80 du 7,62 mm, la profondeur de pénétration et le volume du cratère ont été examinés en fonction du paramètre d'érosion. Pour les paramètres d'érosion variant de 0,5 à 3,0 on a constaté une dépendance significative des résultats de pénétration. Pour les paramètres d'érosion supérieurs à 3,0, la plupart des résultats de la pénétration correspondent aux résultats expérimentaux.

105-01822/

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EXECUTIVE SUMMARY

During the high velocity penetration that takes place where a projectile strikes a target, many significant phenomena appear to be experimentally intractable due to the complexity of materials deforming at extremely high strain rates. To better understand the physics of the penetration process during high velocity impact, hydrodynamic computer simulations (hydrocodes), using finite element analysis methods, have proven to be an invaluable diagnostic and design tool.

Literature has shown that, in general, very good agreement between hydrocode modelling, experiments and theory can be obtained but care must be taken in the definition of the problem from the numerical and material modelling standpoints. In addition to defining an adequate finite element mesh, an important aspect of conducting successful penetration simulations is the use of adequate material failure models. This latter aspect can be difficult because current methods used to model penetration include an erosion strain within the constitutive model. This erosion strain is used to remove an element when it is severely distorted within the mesh. However, this erosion parameter is user-dependent and non physical and therefore must be selected by the user based on intuition or experience. Extreme care has to be taken in its definition in order to obtain realistic numerical results.

In this study, an attempt is made to examine the effect of the erosion strain on the prediction of the ballistic limit of a 10.8-mm thick 6061-T6 aluminium plate struck by a SS109 5.56-mm bullet and the depth of penetration of a semi-infinite aluminium target struck by a M80 7.62-mm bullet. The results obtained show that it is possible to have some control on the erosion strain and obtain excellent results when conducting predictive studies. In addition, the results of this will improve DND's numerical prediction capabilities and help guide experimental studies, particularly given the large amount of resources required to perform terminal ballistics experiments.

LIST OF SYMBOLS

ρ	density
E	elastic modulus
ν	Poisson's ratio
σ_y	yield stress
E_t	tangent modulus
f_s	failure strain
DOP	depth of penetration
V_{100}	ballistic limit
V_i	impact velocity
RHA	rolled homogeneous armour

1.0 INTRODUCTION

In armour design applications, the extent to which projectiles travelling at high velocity are able to penetrate armour systems of different compositions and thicknesses is obviously the driving factor. When both projectile and target materials are deforming hydrodynamically, the penetration problem becomes extremely complex to analyse either analytically or experimentally. This complexity is mainly due to the interaction of the dynamic properties of the two materials. Approximate solutions are usually all that can be obtained.

In recent years, hydrocode simulation has proven to be a useful tool for solving the design problems that involve the complexities described above. These hydrocodes are large computer programs that can be used to simulate numerically highly dynamic events, particularly those which include shocks, by approximating a continuum in a pointwise or piecewise manner. The conservative equations coupled with material descriptions are then solved. As pointed out by Anderson and Bodner in their review (Ref. 1), hydrocode enhancements have evolved as a result of the need for researchers to improve predictive capabilities. These enhancements are the result of a combination of numerical techniques and the inclusion of physically based constitutive models. The first numerical simulations of impact and penetration investigated hypervelocity impact and the formulations did not include material strength effects. Metals for example, were treated as fluids. Zukas (Ref. 2) gives a short history on the evolution and development of hydrocodes, particularly with respect to impact problems. It has been found that in numerical simulations of penetration events, as well as other dynamic scenarios, a method must be developed where the continuum is modified to permit fracture, stress relaxation, the introduction of new free surfaces and other manifestations of material failure. Anderson and Bodner (Ref. 1) further explain that computational modelling of failure has been limited to a single failure mode and the primary reason for this limitation is that modelling failure requires a model for it as well as a method for representing failure and

failure propagation in the calculation grid. The latter requirement has probably been the more dominant challenge in numerical simulation. To overcome this dominant difficulty, most hydrocodes numerically use the concept of erosion (element deletion) to simulate total material failure. Erosion occurs when the equivalent plastic strain exceeds a user-prescribed erosion strain, f_s.

In this document, the sensitivity of the penetration results to erosion strain is examined. This work was performed at DREV between May and October, 1998 under Work Unit 2fa23, Tactical Vehicle Systems Thrust, Protection Project, "Numerical Modelling of Ballistics Events".

2.0 OBJECTIVE

In order to develop better experimental procedures that would optimise penetration results from experiments, DREV has been conducting extensive numerical simulations of terminal ballistic events. However, it has been observed that in addition to the finite element mesh, the predicted penetration results are very sensitive to the erosion strain which allows material to fail numerically.

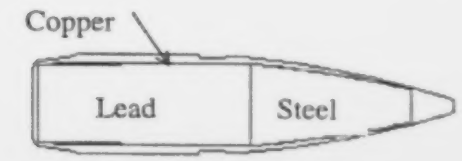
The primary objective of this work is to use two different projectile/target systems to examine the effect of varying the erosion strain on the predicted penetration results.

3.0 NUMERICAL SIMULATIONS

LS-DYNA2D (Ref. 3), a hydrodynamic finite element computer code, was used to simulate the impact of two different projectiles on aluminium and steel targets. The LS-DYNA2D hydrocode is an explicit two dimensional lagrangian finite element code used for analysing the large deformation and high strain rate response of inelastic structures.

3.1 Projectile and Target Description

In this study two projectile/target systems were used to conduct the erosion strain investigation. In the first system the projectile is the SS109 5.56-mm semi-armour piercing bullet striking a 10.8-mm 6061-T6 aluminium target while for the second system, the projectile is the M80 7.62-mm bullet striking a 76.2-mm thick semi-infinite aluminium target. Figure 1 shows the main features of the 5.56-mm SS109 and 7.62-mm M80 bullets. Examination of the main features shows that the M80 7.62-mm bullet has an all lead core, whereas the SS109 5.56-mm two-piece core consists of lead and steel.



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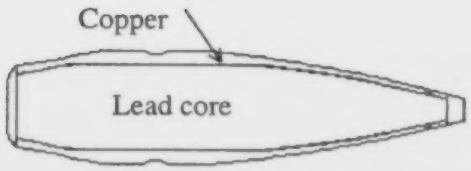

(b)

FIGURE 1 – Main features of the projectiles used in this study. (a) SS109 5.56-mm lead/steel core bullet, (b) M80 7.62-mm lead core bullet

3.2 Numerical Mesh

To model the impact, penetration and deformation processes occurring when the projectile impacts the target and the subsequent deformation of the plate, it is necessary to divide the plate and the projectile into a finite number of regions called elements. The

network of elements obtained is called a mesh. The computations are then performed by solving the constitutive equations for the deformation of the individual elements in the mesh.

In this study, two approaches were used to conduct the investigation on the effect of the failure strain on the ballistic performance. The first approach involves the SS109 5.56-mm bullet striking a finite thickness aluminium plate. The second approach uses a semi-infinite aluminium target struck by the M80 7.62-mm bullet. Figures 2 and 3 show typical finite element meshes that were used to model the two systems.

FIGURE 2 – SS109 5.56-mm bullet striking a 10.8-mm aluminium target

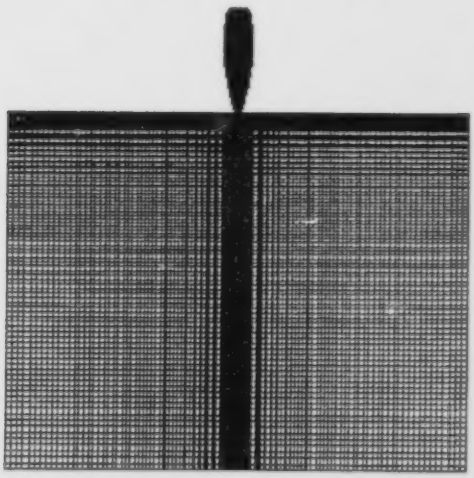

FIGURE 3 – M80 7.62-mm bullet striking a semi-infinite aluminium target

Nandlall (Ref. 4) discusses the concept of a semi-infinite target. Basically, a semi-infinite target is one for which the boundaries are remote enough that the reflected shock waves do not return to the penetrator/target interface until the penetration process is completed. Because of the large amount of CPU time required to obtain a solution to the problem, an iterative process was employed to minimise the dimensions of the target. The approach used is discussed in detail by Nandlall (Ref. 4). For both the finite thickness case and the semi-infinite case, the meshes, shown in Figs. 2 and 3 respectively, were considered as the initial time just as the projectile impacts the target.

In order to conduct a realistic simulation of the impact problem, the finite element mesh needs to be relatively dense in regions that will experience high stress gradients and large deformations. Due to the axisymmetric nature of the problem studied, only half of the domain was considered. 4-node 2D axisymmetric shell elements were used throughout the mesh. Table I shows the element distribution for the two different projectile/target systems studied.

TABLE I

Element distribution for the projectile/target systems studied

Projectile/Target Type	Number of Elements		Total Number of Elements
	Projectile	Target	
SS109 5.56-mm /10.8-mm thick aluminum target	673	639	1312
M80 7.62-mm/semi-infinite aluminum target	876	5400	6276

Figures 2 and 3 show that relatively coarse meshes were constructed at the outer regions of the geometries, far from the impact zone. This was done in order to minimise the computational time which could otherwise be very large. For this study, a simple mesh sensitivity analysis was conducted. The mesh size was adjusted until the penetration results did not vary significantly as the mesh density was changed. The result

was an optimum mesh size that was subsequently used for all the simulations performed in this study. Nandlall and Wong (Ref. 5) discuss in detail the necessity of using an optimised finite element mesh for conducting penetration studies.

3.3 Material Models

For all the simulations, a kinematic/isotropic elastic-plastic hydrodynamic constitutive model was used for both the projectile and target. The model assumes a bi-linear stress-strain behaviour of the material while the strain rate is accounted for very simplistically through a scaling factor applied to the yield stress. Nandlall and Wong (Ref. 5) have used this model extensively to simulate similar projectile/target systems and have shown that a constitutive model of this type is capable of reproducing experimental results with good accuracy. The parameters used for both the projectile and target materials are given in Table II.

TABLE II

Material properties used for LS-DYNA2D model

Material Parameters	Projectile Material			Target Material
	Lead	Steel	Copper	Aluminium
Density, ρ (g/cm^3)	11.35	7.83	8.960	2.768
Elastic Modulus, E (Mbars)	0.1379	0.0121	1.232	0.7309
Poisson's Ratio, ν	0.42	0.30	0.38	0.34
Yield Stress, σ_y (Mbars)	0.00011	0.02	0.0042	0.0034
Plastic Modulus, E_t (Mbars)	0.0	0.02	0.0	0.00646

For all the material models used in this study, the frictional forces between the materials in contact were ignored. It was assumed that, the hydrodynamic pressure dominates the effects of the other forces during the penetration process and, therefore, the frictional forces between the projectile and target are negligible.

3.4 Ballistic Performance Evaluation

Two procedures are used to evaluate the ballistic performance of the two projectile/target systems used in this study.

For the finite thickness target, the ballistic limit method is employed. The ballistic limit is defined as the minimum striking velocity which is required to completely perforate a target. This limit is sometimes called the V_{100} limit which, in experimental terms, is the minimum striking velocity at which the projectile will always perforate the target. Because of the large number of simulations required in this study, a simple technique was employed to obtain the ballistic limit. A simulation was conducted with a projectile striking velocity that would ensure that the target would be perforated. The successive striking velocities of the projectile were reduced until the projectile did not perforate the target. The ballistic limit was taken as the striking velocity which, when increased or decreased by 3 m/s, will result in the target being perforated or not perforated, respectively.

In the case of the projectile/semi-infinite target system, the depth of penetration and crater volume method is used to examine the effect of the failure strain on the ballistic performance. This method involves using a range of projectile striking velocities and evaluating the depth of penetration and crater volume as a function of the impact velocity.

4.0 COMPUTATIONAL RESULTS AND DISCUSSIONS

Figure 4 shows an example of a typical simulation that was performed for the SS109 5.56-mm projectile/target system in an effort to obtain the ballistic limit against the aluminium plate. In this case the lead part of the core was completely eroded and the back end of the copper liner remained in the hole. The steel part of the core did not deform significantly. In this case the projectile striking velocity was 480 m/s.

Simulations similar to the example shown in Fig. 4 were conducted to obtain the ballistic limit of the target for different target material erosion strains. Figure 5 shows the ballistic limit, V_{100}, as a function of the erosion strain, f_s.

FIGURE 4 – Penetration profile of the SS109 5.56-mm bullet striking a 10.8-mm aluminium target (V_i=480 m/s)

A close examination of the graph shown in Fig. 5 reveals that the ballistic limit increases significantly as the erosion strain is increased above 0.4. This continues until the erosion strain reaches approximately 1.3 after which the ballistic limit is observed to become less and less dependent on the erosion strain.

In the case of the 7.62-mm M80 bullet the lead core is much more ductile than the relatively higher strength aluminium target material. As a result, it was anticipated that variation of the erosion strain of the lead would affect the depth of penetration and crater size to a greater extent.

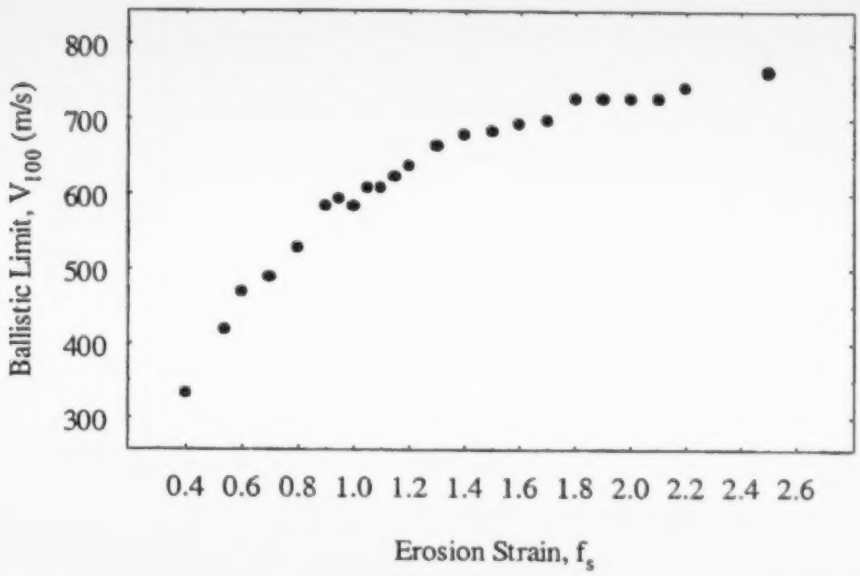

FIGURE 5 – Ballistic limit variation as a function of erosion strain, f_s, for the SS109 5.56-mm bullet/finite thickness target system

Since experimental results were available for an impact velocity of 817.5 m/s it was decided to conduct the simulations with this impact velocity while varying the erosion strain for the lead core. Figure 6 shows a typical final penetration profile which in this case is for an erosion strain of 5.0.

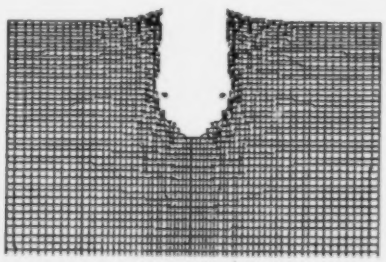

FIGURE 6 – Penetration/crater profile of the aluminium semi-infinite target struck by a M80 7.62-mm bullet at 817.5 m/s.

Figure 7 shows the depth of penetration (DOP) as a function of the erosion strain of the lead core of the M80 7.62-mm bullet. Over the range of erosion strains simulated, it is observed that between $f_s = 0.5$ and $f_s = 2.0$ the DOP increases as the erosion strain increases. However, between $f_s = 3.0$ and $f_s = 7.0$ a curve with a small positive slope is obtained and the DOP varies between 1.65 and 2.0 cm. These results suggest that over this range of erosion strains the variation of the DOP is less sensitive to the choice of f_s.

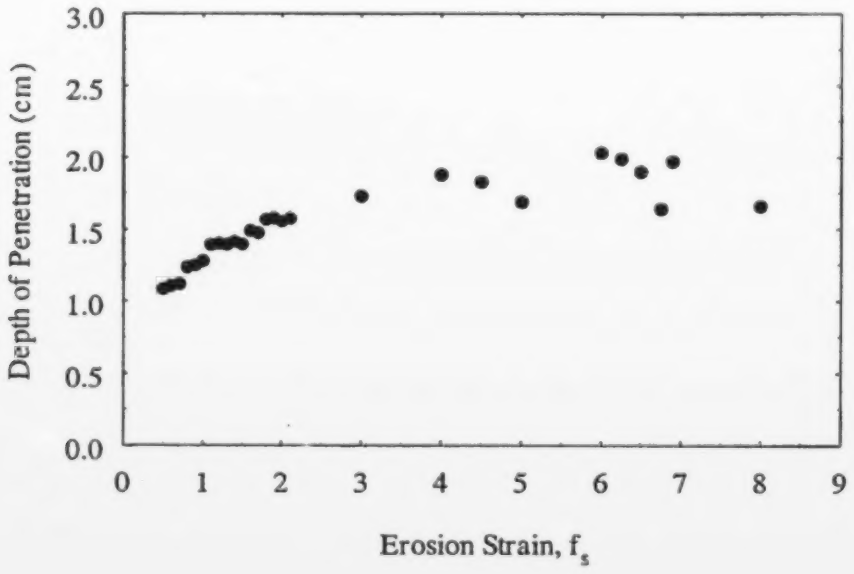

FIGURE 7 – Depth of penetration, DOP, as a function of erosion strain, f_s, for the case of a M80 7.62-mm striking a semi-infinite aluminium target

Figure 8 shows the crater volume as a function of the erosion strain, as obtained from the simulations. The experimental value is represented by the dashed line. In this figure it is seen that the crater volume also increases as a function of the erosion strain between the range of $f_s = 0.5$ and $f_s = 2.0$ after which the crater volume approaches the experimental value as the erosion strain is increased. The mechanics of crater formation is an important aspect of high velocity penetration.

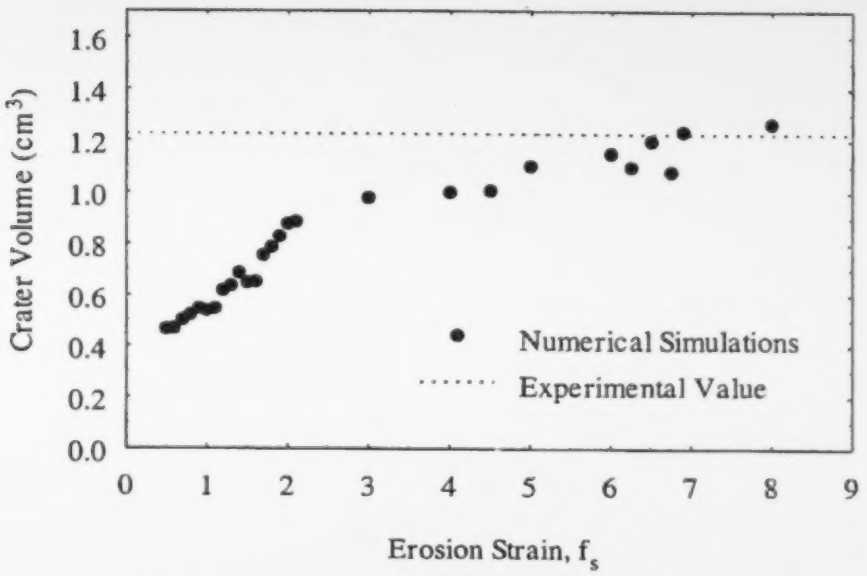

FIGURE 8 – Crater volume as a function of erosion strain for case of the 7.62-mm bullet penetrating a semi-infinite aluminium target

Figure 9 shows the crater profiles obtained using four different erosion strains. Nandlall (Ref. 4) examines this aspect of crater formation. The geometry of the craters exhibits one notable feature: the diameter of the entry hole is smaller than the bottom of the crater. This feature is more distinct as the erosion strain increases and basically conforms to the deformation hypothesis proposed by Brooks (Ref. 6). This phenomenon of the entry hole diameter being smaller than that at the bottom of the crater is due to the mushrooming effect of the projectile as it penetrates the target. As the projectile erosion strain increases the mushrooming of the projectile becomes more and more pronounced thereby causing the crater bottom to become larger. During the initial stages of penetration, stresses are built up in the material around the projectile/target interface. This, coupled with the mushrooming effect, tends to decrease the stresses on the target and allows more of the target to interact with the projectile. Large hydrodynamic stresses occur in the target because the target material around the crater is confined by the surrounding material. These stresses are transmitted to the projectile whose nearby free surfaces are accelerated radially. In the present case of the M80 7.62-mm bullet, the

projectile material is relatively ductile and, as a result, the deformation in the radial direction is increased. When the shear forces are exceeded, the mushrooming effect causes the crater to widen. This aspect of crater development is significant as it illustrates the fact that for cases where the projectile is more ductile than the target, most of the work done by the penetrator goes into the crater formation rather than in increasing the depth of penetration.

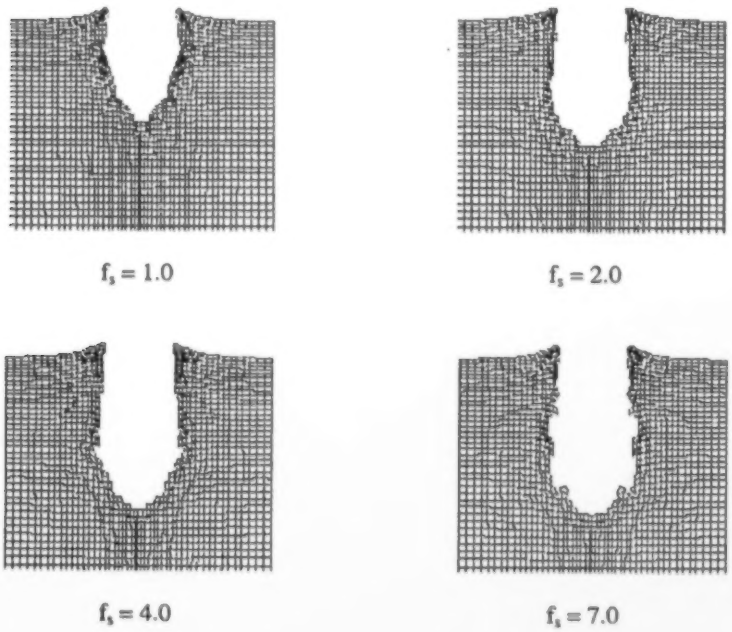

FIGURE 9 – Crater volume/shape comparison for four different erosion strains for the M80 7.62-mm projectile/semi-infinite aluminium target system

5.0 CONCLUSIONS

This study examines the effect of the erosion strain on the penetration results using two different projectile/target systems. The first system consists of the SS109 5.56-mm bullet striking a 10.8-mm 6061-T6 aluminium target while the second system consists of the M80 7.62-mm bullet striking a 76.2-mm semi-infinite aluminium target. In both cases, optimised finite element meshes were used to conduct the penetration studies.

In the case of the SS109 5.56-mm projectile striking a finite thickness aluminium target, it was found that the ballistic limit increased significantly as erosion strain is increased from $f_s = 0.4$. The ballistic limit continues to increase until the erosion strain reaches about 1.3 after which it is observed that the ballistic limit becomes less and less sensitive to f_s.

In the case of the M80 7.62-mm projectile striking the semi-infinite aluminium target, both the depth of penetration and crater volume were examined as a function of the erosion strain. For erosion strains ranging from $f_s = 0.5$ to $f_s = 3.0$ a significant dependence of the penetration results on the erosion strain was observed. For erosion strains above 3.0 some scatter was observed but, in general, it was seen that the penetration results were within the range of the experimental values. In the M80 case, it seems better to examine the crater volume as a function of the erosion strain rather than the depth of penetration as a function of the erosion strain. This is mainly due to the relatively ductile projectile material when compared to the target material, which causes an increase in crater volume rather than a substantial increase in the depth of penetration.

The results of this study illustrate the need for a properly implemented physically based failure model in hydrocodes. Numerous reviews have shown that this is not an easy task. However, notwithstanding this difficulty, the study shows that excellent results can still be obtained but added to the use of appropriate constitutive models, care has to be taken in description of the finite element mesh and the erosion strain which allows penetration to occur during an impact event.

6.0 ACKNOWLEDGEMENTS

Special thanks are addressed to Dr. Kevin Williams, Messrs. Richard Delagrave and Alfred Jeffrey for the many comments with regard to numerical simulations performed, as well as for the revision of this document.

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This memorandum examines the effect of the erosion strain parameter on the numerical simulation results of the penetration of two different projectile/target systems. This parameter permits the failure of the material and numerically allows the penetration of the target. The first system examined consists of the SS109 5.56-mm bullet striking a 10.8-mm 6061-T6 aluminium target while the second system consists of the M80 7.62-mm bullet striking a 76.2-mm semi-infinite aluminium target. For the SS109 5.56-mm case, it was found that the ballistic limit increased significantly as the erosion strain is increased above 0.4, but as it reaches about 1.3, it becomes less and less dependent on the erosion strain. In the case of the M80 7.62-mm projectile, both the depth of penetration and crater volume were examined as a function of the erosion strain. For erosion strains ranging from 0.5 to 3.0 a significant dependence of the penetration results on the erosion strain was observed. For erosion strains above 3.0, most of the penetration results were observed to be within an acceptable range of the experimental value.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Finite Element
Dyna
High Velocity Impact
Fragment
Ballistic Impact
Protection
Numerical Simulation
Hydrocode Simulation

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